Epidemiology / Épidémiologie

Climate change and plant diseases in Ontario

G.J. Boland, M.S. Melzer, A. Hopkin, V. Higgins, and A. Nassuth

Abstract: Current models predict that expected climate change in Ontario will significantly affect the occurrence of plant diseases in agriculture and forestry in the coming years. Direct, multiple effects on the epidemiology of plant diseases are expected, including the survival of primary inoculum, the rate of disease progress during a growing season, and the duration of epidemics. These effects will positively or negatively influence individual pathogens and the diseases they cause. Changes in the spectra of diseases are also anticipated. Abiotic diseases associated with environmental extremes are expected to increase, and interactions between biotic and abiotic diseases might represent the most important effects of climate change on plant diseases. The management of plant diseases will also be affected. In agriculture, plant breeding programs are expected to adapt many crops to increased duration of growing seasons and, concurrently, to develop drought and stress tolerance. There will be opportunities for new crops and cultivars to be introduced, but effective systems must be in place to detect new pathogens and prevent them from entering with these new crops. Because of the long-lived nature of trees, forests are slow to adapt, and the impact of climate change will have to be considered in forest management plans. Adaptations in agriculture and forestry have been occurring in Ontario for over 100 years, but these may need to occur at an accelerated rate because of rapid changes in climate. It is critical that the infrastructure of agricultural and forestry research remains strong to ensure successful transition and adaptation.

Key words: climate change, plant diseases, epidemiology, Ontario.

Résumé : Les modèles actuels des changements climatiques attendus en Ontario prévoient des effets significatifs sur les maladies qui affecteront les plantes en agriculture et en foresterie au cours des années à venir. Il faut s'attendre à des effets directs et multiples sur l'épidémiologie des maladies des plantes, y compris la survie de l'inoculum primaire, la vitesse de propagation d'une maladie au cours d'une saison et la durée des épidémies. Ces effets influenceront favorablement ou défavorablement chaque agent pathogène et les maladies qu'il cause. Des changements sont aussi prévus dans le spectre des maladies. On s'attend à un accroissement des maladies non parasitaires associées aux extrêmes environnementaux, et les interactions entre les maladies parasitaires et non parasitaires peuvent devenir les plus importants éléments touchant les maladies des plantes à la suite des changements climatiques. La lutte aux maladies des plantes sera aussi touchée. En agriculture, on s'attend à ce que les programmes d'amélioration génétique cherchent à adapter plusieurs cultures à des saisons de croissance qui s'allongent et, en parallèle, à développer de la tolérance à la sécheresse et aux stress. Il y aura aussi des occasions pour l'introduction de nouvelles cultures et de nouveaux cultivars, mais des systèmes efficaces devront être en place pour détecter les nouveaux agents pathogènes et les empêcher d'entrer avec ces nouvelles cultures. À cause de la longue durée de vie des arbres, les forêts sont lentes à s'adapter, et l'impact des changements climatiques devra être pris en compte dans les plans d'aménagement des forêts. Des adaptations aux changements en agriculture et en foresterie ont eu lieu, en Ontario, au cours des 100 et quelques dernières années, mais elles devront se produire à un rythme accéléré à cause des changements rapides dans le climat. Il est essentiel que l'infrastructure de la recherche agricole et forestière reste forte afin d'assurer une transition et une adaptation réussies.

Mots clés : changements climatiques, maladies des plantes, épidémiologie, Ontario.

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Introduction

The potential consequences of climate change are receiving increased attention, because there is growing concern over the effects of higher temperatures associated with increasing CO_2 levels in the atmosphere. The final report of the Standing Committee on Agriculture and Forestry (Senate of Canada 2003) entitled *Climate Change: We Are at Risk* contains the following prediction:

> Historically, changes in climate have occurred at a slow enough pace that humanity has been able to adapt to them without major disruptions. There is strong evidence, however, that climate change will accelerate during the coming century at rates beyond our historical ability to adapt.
>
> (Senate of Canada 2003)

CO_2 levels have risen by 30% since the mid-19th century (Barnola et al. 1995) and, in Ontario, an increase of 3 °C in the mean annual temperature over the next century is expected (Griefenhagen and Noland 2003). Temperatures are expected to increase more in winter than in summer, likely increasing the number of frost-free days, and will increase more in northern than in southern latitudes. Minimum temperatures will increase more than maximum temperatures. In association with this warming trend, there are expected changes in precipitation patterns and an increase in extreme weather events. These extreme events include severe drought, high and rapidly fluctuating temperatures, ice storms, and severe wind, rain, and hail storms. Precipitation, though somewhat unpredictable, is expected to increase in Ontario. Although precipitation might increase, increased evapotranspiration due to warmer temperatures will result in drier conditions during the growing season.

Plant health is, and should be, a national priority of Canada because of our economic and environmental reliance on agriculture and forestry. In Ontario, plant agriculture and forestry are major sectors of the economy, but little attention has been given to the effects of climate change on plant health. The ideas presented here summarize the deliberations of a group convened by the Ontario Ministry of the Environment to document the expected effects of climate change on plant diseases in Ontario (Boland et al. 2003). Other groups documented the effect of climate change on animal and human health (Griefenhagen and Noland 2003). Each report used the same predicted climate-change parameters, with the values used approximating the minimum now predicted (Kling et al. 2003). Over the next 100 years, the average annual temperature in Ontario is expected to increase by 3 °C, although more in the winter than the summer; precipitation is expected to increase, although regional and seasonal changes are difficult to predict; and there will be an increased frequency of extreme weather events (Griefenhagen and Noland 2003). Although the suggested changes in plant diseases discussed in this report are based on conditions in Ontario, the general principles considered here are expected to apply to most areas of Canada.

The amount of land devoted to agriculture in Ontario, most of which is located in southern Ontario, is approximately 6×10^6 ha and produces crops with a gross annual value of more than 9×10^9dollars. These crops are well adapted to typical or average growing season conditions, but are susceptible to extreme conditions. The expected change in mean annual temperature of 1 or 2 °C is rarely considered a problem. However, even small changes in the value of the mean involve a change in the frequency and magnitude of extreme conditions. For example, severe drought, which currently has a probability of occurring once every 30 years, might become a once in 4- or 5-year event (Smit 1999[2]). Changes in long-term climatic variability, or simply shifts in extremes, might well have greater impact than changes in climatic averages (Smit and Brklacich 1992).

Crop yields are significantly impacted every year in Ontario, and elsewhere, by diseases. The effects of climate change on crop health and, in particular, on crop disease are not known. Crops are expected to benefit from warmer temperatures and elevated levels of CO_2 in the atmosphere, but might be stressed by drier soils and weather extremes. Stressed plants are often more susceptible to disease. In addition, pathogens that cause crop diseases will be influenced directly by changes in climate, positively or negatively, depending on the environmental conditions that they require to cause disease.

Because of the long-lived nature of forests, climate change that occurs over a relatively short period of time can have serious consequences to forest health. Ontario is dominated by forest, which makes up 74% of the land cover. It has over 58×10^6 ha or 14% of Canada's forested area (Natural Resources Canada 2002). Warmer and, most likely, drier climate conditions can be expected to affect Ontario's forests directly (Colombo and Buse 1998). However, the indirect impacts on forests of changes in disturbance patterns are possibly even greater. Under future scenarios, variable and extreme weather conditions will be more common, and more frequent fires are anticipated in Canada, particularly in the boreal forest that makes up the majority of Ontario's land (Stocks et al. 1996, 1998).

In terms of biotic disturbances, considerable thought has been given to anticipating the impact of climate change on insect populations and associated damage in forestry (Harrington et al. 2001; Volney and Fleming 2000). By contrast, there has been little discussion on the potential impact of climate change on tree diseases and their subsequent impact on forests, although the link between climate and forest diseases is well known (Hepting 1963). In Ontario's forests, over 20×10^6 m^3 of wood are annually lost to diseases, including decay fungi (Gross 1991). A number of these diseases respond to stresses, which make trees more susceptible to infection. In forests, diseases also interact with insects and abiotic stresses, resulting in forest declines (Manion and Lachance 1992).

Typically, the two most important environmental factors in the development of plant disease epidemics are temperature and moisture (Agrios 1997). In temperate regions, such as Ontario, the majority of plant pathogens are not active in late fall, winter, and early spring because of low temperatures. Some diseases are favoured by cool temperatures, while others are favoured by moderate or hot conditions. Disease often occurs when temperatures are more stressful

[2] Smit, B. 1999. Agricultural adaptation to climate change in Canada: a report to the Adaptation Liaison Office.

for the plant than for the pathogen. Moisture, in the form of free water or high humidity, is necessary for infection, reproduction, and spread in many plant pathogens, although some pathogens cause disease in dryer conditions. Because environmental conditions favourable to disease development vary greatly among plant pathogens, it is vital to understand the environmental requirements of individual plant pathogens before predictions on responses to climate change can be made.

Climate change and plant diseases

The literature provides some background on the potential impact of climate change on plant diseases. Much of this literature focuses on diseases of agricultural crops and includes discussion of the influence of temperature, precipitation, carbon dioxide, ozone, ultraviolet (UV) radiation, and insects on plant diseases (Chakraborty et al. 1998a, 1998b; Coakley 1995; Coakley et al. 1999; Harvell et al. 2002; Manning and Tiedemann 1995; Porter et al. 1991; Sandermann 2000). Most of the predicted effects of changes in these environmental factors on plant pathogens are relatively intuitive to plant pathologists, but predicting their effect on plant diseases per se requires greater knowledge of how these factors affect the physiology of the host plant and, consequently, the host–pathogen interaction. Therefore, more clarifications are needed for effects of elevated CO_2, UV radiation, and ground-level ozone, as well as for effects of environmental changes on insect vectors.

The effect of increased CO_2 on the host and the pathogen and the interaction of these factors have not been well studied. CO_2 concentrations in the troposphere are projected to increase from 355 ppm (*v*/*v*) to 710 ppm by the year 2050 (Manning and Tiedemann 1995). It is expected that higher CO_2 concentrations will result in increased plant biomass production due to increased photosynthesis, where there is sufficient soil moisture. These increases in CO_2 will probably have little direct effect on most pathogens, as many soil-inhabiting fungi can tolerate more than 10- or 20-fold increases in CO_2, and might even be slightly stimulatory (Manning and Tiedemann 1995). Chakraborty et al. (1998a) suggest that the impact of increased CO_2 concentrations on plant diseases will likely be through changes in host physiology and anatomy, such as lowered nutrient concentration, greater accumulation of carbohydrates in leaves, more waxes, extra layers of epidermal cells and increased fiber content, and greater number of mesophyll cells. There are indications that decomposition of leaf litter formed at higher CO_2 occurs more slowly (Coakley et al. 1999). Greater biomass, slower decomposition, and increased pathogen survival due to milder winters would result in increased initial inoculum available to infect subsequent crops (Coakley et al. 1999). Coakley et al. (1999) reported that two important trends have emerged in the effects of elevated CO_2 on host–pathogen interactions: (1) initial establishment of a pathogen may be delayed because of modifications in pathogen aggressiveness and (or) host susceptibility and (2) increased fecundity of pathogens. The combination of increased fecundity and a more humid microclimate within dense crop canopies associated with increased CO_2 concentrations might provide more opportunities for severe infection.

Changes in the intensity and quality of UV radiation as a result of thinning of the ozone layer is another factor that had received minimal attention in relation to plant diseases. Ultraviolet light is known to stimulate sporogenesis in fungi but can also reduce survival of spores during dispersal and early stages of infection (Paul et al. 1998). Manning and Tiedemann (1995) pointed out that an increase in solar UV-B radiation would likely promote sporulation, but that normal daylight already contains sufficient UV radiation to stimulate sporulation of light-dependent fungi. They concluded that the expected increase in UV radiation is not sufficient to significantly affect the life cycles of plant-pathogenic fungi.

Our perceptions of the effects of elevated ozone levels on plant diseases also require reevaluation. Ozone levels in Ontario often exceed 85 ppb, which is 20 points above the target in Ozone Annex of the 1991 Canada – United States Air Quality Agreement (Environment Canada 2003). Areas along the shore of Lake Huron have reached levels of 138 ppb. Ozone levels in the summer increased by 0.5% per year from 1980 to 1998, with rural areas often seeing the largest increases. Previously, it was believed that periods of high ozone concentration did not coincide with environmental conditions suitable for infection by most fungal pathogens, and this implied minimum interactive risk. However, it is now known that ozone-induced metabolic changes can persist in plants over days or months. Both increased (Karnosky et al. 2002; Rist and Lorbeer 1984; Sandermann 2000) and decreased (Coleman et al. 1987, 1988) disease susceptibility in plants, following ozone exposure, have been reported.

Insects are important vectors of many plant diseases, and the potential effects of climate change on agricultural insect pests have been explored by Porter et al. (1991). Temperature is the most critical climatic variable for insects. Low temperature extremes can significantly increase mortality, while higher winter temperatures have the potential to increase the survival of many overwintering species, and may allow changes in species distribution (Porter et al. 1991). Higher temperatures in spring and summer could result in faster development rates and, therefore, more rapid increases of pest populations. Such effects would be particularly important in spring, where current temperatures are a limiting factor for development and distribution (Porter et al. 1991).

Increases in food availability as a result of plant stress due to environmental extremes might result in increases in development rates of insect pest populations (Rhoades 1985). Pest outbreaks are more likely to occur with stressed plants, because reduced resistance in plant hosts can lead to increased food and breeding site availability, particularly in tree species.

Climate change and plant diseases in Ontario

In assessing the potential impact of climatic assumptions on plant diseases for Ontario, three key stages of the disease cycles of the most prevalent and economically important diseases of agricultural and forestry species in Ontario were considered. Additional diseases were included when there was evidence that minor diseases might change their relative prevalence or severity under the assumed climate-change model for Ontario. These results are summarized in Table 1.

The three disease stages that were assessed included survival of primary inoculum of the pathogen, rate of disease progress during a growing season, and the duration of the annual epidemic in relation to the host plant (Zadoks and Schein 1979; Leonard and Fry 1986). The effect of climate change on each of these components and the anticipated effect this would have on disease severity were assessed for each disease. In all cases, explanatory remarks were included in the summary table to indicate the most important factors considered for each disease (Table 1). Reasons for anticipated effects are listed first for primary inoculum and disease establishment, and then, following a semicolon, for rate of disease progress. The duration of epidemics is expected to increase or remain the same, depending on the host plant. Some crops, such as corn and soybeans, will be developed to take advantage of the longer growing season, and this will result in an increase in yield and duration of epidemics. In other crops, such as fresh-market vegetables, additional growing time may not be an advantage, because early maturing crops often have more market advantage than total yield. However, in these crops, overlapping planting dates within the same field may still effectively prolong the presence of susceptible hosts and, therefore, also prolong the duration of epidemics. The overall estimated effect of changes in climate on each disease is indicated in Table 1. In many cases, these assessments were necessarily subjective, but to illustrate them in more details, several examples were selected and presented (see examples 1 to 8 in Appendix).

The predicted effects of climate change on diseases of selected major agricultural and forestry species in Ontario (Table 1) include only those diseases already present in Ontario, i.e., this assessment does not take into account alien species of plant pathogens, although the potential for new introductions under a changing climate is well known (Baker et al. 2000).

Fungal diseases

Within plant-pathogenic fungi, there are representatives of several primary-inoculum types (Agrios 1997; Lucas 1998; Trigiano et al. 2004). Soilborne fungi survive in soil by producing structures such as sclerotia or thick-walled spores (e.g., chlamydospores or oospores). Soilborne fungi include species of *Botrytis*, *Fusarium*, *Phytophthora*, *Pythium*, *Rhizoctonia*, *Sclerotinia* (example 1), *Sclerotium*, and *Verticillium*. Survival structures produced by soilborne fungi are persistent and can survive for years in soil, therefore, the milder winters and reduced soil moisture expected in Ontario with climate change are not expected to significantly affect their survival.

Host- or debris-borne fungi overwinter and produce primary inoculum on infected tissues of perennial plants and on plant debris of annual plants. Fungi of this type include *Alternaria*, *Cercospora*, *Colletotrichum*, *Erysiphe*, *Phaeoisariopsis* (example 2), *Phomopsis*, *Septoria*, and *Venturia* species. Milder winters in Ontario are expected to result in increased survival of these pathogens.

Several important introduced fungal pathogens do not survive Ontario winters, and their source of primary inoculum is infected seed, or spores in air currents from the south. Fungi of this type include *Peronospora tabacina*, *Puccinia* spp. on cereals, and *Ustilago tritici*. Milder winters in Ontario might allow some overwintering of these pathogens or, more likely, earlier migration resulting in earlier infection and, therefore, longer epidemics.

Monocyclic fungal diseases, such as those caused by *Ustilago* and *Sclerotinia* species, are not expected to be affected by climate change as much as polycyclic diseases. In polycyclic diseases, such as those caused by *Colletotrichum*, *Peronospora*, *Phytophthora*, and *Puccinia* species, each additional disease cycle multiplies inoculum manyfold, so an increased duration of the growing season in Ontario would be expected to result in an increased number of disease cycles and inoculum. On the other hand, the effect of a longer growing season on polycyclic diseases might be counteracted by drier summers. In contrast, monocyclic vascular wilts and root rots will result in more severe disease symptoms as the result of increased drought stress.

Moisture, in the form of rain, dew, or high humidity, is the most important factor in the development of most epidemics caused by fungi. High levels of moisture promote infection and sporulation and facilitate spore release and germination in many fungi (Agrios 1997). Prolonged or repeated high moisture conditions lead to epidemics. Most fungi are active over a range of temperatures, but activity is highest at moderate temperatures (18–24 °C). With adequate moisture and optimum temperatures, polycyclic fungi can complete their disease cycles quickly, often within several days. Overall, with a trend toward warmer, drier summers, plant diseases caused by fungi are expected to decrease. There might be little change in disease levels in the spring and fall, when moisture is more abundant, but disease progress is expected to slow in the warmer, drier summer months. A reduction in the number of disease cycles for polycyclic diseases and a slowing in the progress of some monocyclic diseases will result in reduced primary inoculum for the next season. On the other hand, there are some fungal plant pathogens, such as *Podosphaera*, *Sphaerotheca*, *Uncinula*, and *Ustilago* species, that thrive in warmer, drier conditions (Agrios 1997; Trigiano et al. 2004), and these are expected to increase in significance in Ontario with expected climate changes.

In the case of fungal pathogens of forest tree species, many native pathogens can cause general damage over a wide area as evidenced by root rots (e.g., armillaria and tomentosus root rots), decay fungi, and many of the canker-causing diseases (e.g., hypoxylon canker of poplar). Ontario forests are also susceptible to introduced diseases such as Dutch elm disease, beech bark disease, and white pine blister rust that have caused serious damage and threaten individual tree species over a broad area. Recently, there have been losses to individual tree species due to new pathogens such as *Phytophthora ramorum* Werres, DeCock & Man causing sudden oak death in California and Oregon, which potentially also threatens red oak (*Quercus rubra* L.) in Ontario given appropriate environmental conditions (Garbelotto

Table 1. Anticipated effects of climate change on selected diseases of prevalent crop and forest species in Ontario.

Crop and disease	Pathogen (group)[a]	Effect of climate change[b]: Primary inoculum or disease establishment	Rate of disease progress	Potential duration of epidemic[c]	Reasons for effects[d]	Net effect on disease[e]
FIELD CROPS						
Alfalfa (*Medicago sativa* L.)						
Anthracnose	*Colletotrichum trifolii* (F)	+	—	–	B;EO	–
Damping-off	*Pythium* spp. (F)	–	—	–	B;EK	– –
Root rot	*Phytophthora megasperma* (F)	–	—	–	B;EK	– –
Verticillium wilt	*Verticillium albo-atrum* (F)	+	—	–	B;GIL	+
Corn (*Zea mays* L.)						
Anthracnose	*Colletotrichum graminicola* (F)	+	—	+	B;E	–
Common smut	*Ustilago maydis* (F)	+	+	+	FL	++
Eyespot	*Kabatiella zeae* (F)	+	—	+	E	– –
Fusarium ear rot	*Fusarium* spp. (F)	+	+	+	B;FL	+
Grey leaf spot	*Cercospora zeae-maydis* (F)	+	+	+	B;EM	+
Northern leaf blight	*Exserohilum turcicum* (F)	+	—	+	B;E	–
Stewart's disease	*Erwinia stewartii* (B)	+	+	+	C;GH	+
Soybean (*Glycine max* (L.) Merrill)						
Brown stem rot	*Phialophora gregata* (F)	+	—	+	AB;EG	–
Downy mildew	*Peronospora manshurica* (F)	–	—	+	D;E	–
Pod and stem blight	*Diaporthe phaseolorum* (F)	+	—	+	B;M	–
Stem canker	*Diaporthe phaseolorum* (F)	+	—	+	B;EM	–
Powdery mildew	*Microsphaera diffusa* (F)	+	—	+	BE	–
Root rot	*Phytophthora sojae* (F)	–	+	+	A;EGK	+
Root rot	*Rhizoctonia solani* (F)	–	+	+	A;GK	+
Sudden death	*Fusarium solani* (F)	–	—	+	A;EI	–
White mold	*Sclerotinia sclerotiorum* (F)	—	—	+	A;EKM	–
Cyst nematode	*Heterodera glycines* (N)	—	+	+	A;FG	++
Tobacco (*Nicotiana tabacum* L.)						
Blue mold	*Peronospora tabacina* (F)	–	—	–	D;EJ	–
Soybean mosaic	*Soybean mosaic virus* (SMV) (V)	–	+	–	D;HI	+
Tobacco ringspot	*Tobacco ringspot virus* (TRSV) (V)	–	+	–	D;HI	+
Winter wheat (*Triticum* spp.)						
Dwarf bunt	*Tilletia controversa* (F)	–	+	–	A	+
Head blight	*Fusarium* spp. (F)	+	—	–	B;EM	–
Leaf blotch	*Septoria tritici* (F)	+	—	–	B;KEM	– –
Leaf rust	*Puccinia recondita* (F)	+	—	–	BD;EM	– –
Loose smut	*Ustilago tritici* (F)	–	—	–	D;E	–
Seedling blight	*Fusarium* spp. (F)	–	+	–	D;G	+
Snow mold	*Microdochium nivale* (F)	—	—	–	B	– –
Snow mold	*Sclerotinia borealis* (F)	—	—	–		– –
Snow mold	*Typhula* spp. (F)	—	—	–		– –
Stem rust	*Puccinia graminis* (F)	–	—	–	D;EM	–
Take-all	*Gaeumannomyces graminis* (F)	+	–	–	B;EGK	–
Tan spot	*Pyrenophora tritici-repentis* (F)	+	—	–	B;EM	–
VEGETABLE CROPS						
Bean (*Phaseolus vulgaris* L.)						
Angular leaf spot	*Phaeoisariopsis griseola* (F)	+	—	–	BD;E	–
Damping-off	*Pythium* spp. (F)	–	—	–	A;K	–
Grey mold	*Botrytis cinerea* (F)	–	—	–	AB;M	–
Pod and leaf spot	*Alternaria alternata* (F)	+	—	–	B;E	–
White mold	*Sclerotinia sclerotiorum* (F)	+	—	–	A;EK	– –
Bacterial blight	*Xanthomonas campestris* (B)	–	–	–	D;EFM	0
Bean common mosaic	*Bean common mosaic virus* (BCMV) (V)	–	+	–	D;HI	+
Bean yellow mosaic	*Bean yellow mosaic virus* (BYMV) (V)	+	+	–	C;HIO	++

Table 1 (*continued*).

Crop and disease	Pathogen (group)[a]	Effect of climate change[b]: Primary inoculum or disease establishment	Effect of climate change[b]: Rate of disease progress	Effect of climate change[b]: Potential duration of epidemic[c]	Reasons for effects[d]	Net effect on disease[e]
Carrot (*Daucus carota* L. subsp. *sativus*) (Hoffm.) (Arcang.)						
Cavity spot	*Pythium* spp. (F)	–	—	–	A;EK	–
Crown rot	*Rhizoctonia solani* (F)	–	—	–	A;EK	–
Leaf blight	*Alternaria dauci* (F)	+	—	–	B;EM	– –
Sclerotinia rot	*Sclerotinia sclerotiorum* (F)	—	—	–	A;EK	–
Aster yellows	Aster yellows phytoplasma (P)	+	+	–	BC;GIJ	+
Onion (*Allium cepa* L.)						
Basal rot	*Fusarium oxysporum* (F)	+	+	–	A;F	+
Damping-off	*Pythium* spp. (F)	–	—	–	A;EK	– –
Damping-off	*Fusarium* spp. (F)	+	+	–	ABC;G	+
Downy mildew	*Peronospora destructor* (F)	–	—	–	D;EM	–
Leaf blight	*Botrytis squamosa* (F)	–	—	–	ABD;EM	–
Pink root	*Phoma terrestris* (F)	+	+	–	A;FGH	+
Smut	*Urocystis colchici* (F)	–	—	–	A;E	–
White rot	*Sclerotium cepivorum* (F)	–	—	–	A;EK	–
Slippery skin	*Pseudomonas gladioli* (B)	–	—	–	A;ELM	–
Soft rot	*Erwinia carotovora* (B)	–	+	–	AB;LM	+
Sour skin	*Pseudomonas cepacia* (B)	–	—	–	A;ELM	–
Potato (*Solanum tuberosum* L.)						
Canker	*Rhizoctonia solani* (F)	+	—	+	AB;E	–
Early blight	*Alternaria solani* (F)	+	—	+	AB;EL	–
Late blight	*Phytophthora infestans* (F)	+	—	+	BD	–
Pink rot	*Phytophthora erythroseptica* (F)	–	—	+	B;K	–
Verticillium wilt	*Verticillium* spp. (F)	+	+	+	A;G	+
Blackleg	*Erwinia carotovora* (B)	–	—	+	ABD;EK	–
Common scab	*Streptomyces scabies* (B)	–	+	+	BD;K	+
Ring rot	*Clavibacter michiganensis* (B)	+	—	+	BD	–
Potato leafroll	*Potato leafroll virus* (PLRV) (V)	–	+	+	BC;HI	++
Sweet corn (*Zea mays* L.)						
Common smut	*Ustilago maydis* (F)	+	+	+	ABD;FL	++
Ear rot	*Fusarium graminearum* (F)	+	+	+	B;FL	+
Northern leaf blight	*Exserohilum turcicum* (F)	+	—	+	B;E	– –
Rust	*Puccinia sorghi* (F)	–	—	+	D;EJM	–
Stalk rot	*Diplodia maydis* (F)	+	+	+	BD;L	+
Stalk rot	*Fusarium* spp. (F)	+	+		B;L	+
Stalk rot	*Pythium* spp. (F)	–	—		B;K	–
Stewart's disease	*Erwinia stewartii* (B)	+	+	+	CD; GH	++
Tomato (*Lycopersicon esculentum* Mill.)						
Anthracnose	*Colletotrichum coccodes* (F)	+	—	–	ABD;LM	–
Early blight	*Alternaria solani* (F)	+	—	–	B;EL	–
Late blight	*Phytophthora infestans* (F)	+	—	–	B;EM	–
Leaf spot	*Septoria lycopersici* (F)	+	—	–	BD;EM	–
Verticillium wilt	*Verticillium* spp. (F)	–	+	–	BD;G	+
Bacterial canker	*Clavibacter michiganensis* (B)	–	+	–	BD;FLM	+
Bacterial speck	*Pseudomonas syringae* (B)	+	—	–	BD;LM	0
Bacterial spot	*Xanthomonas campestris* (B)	+	—	–	BD;LM	0
Cucumber mosaic	*Cucumber mosaic virus* (CMV) (V)	+	+	–	C;GHI	++
Tomato mosaic	*Tomato mosaic virus* (ToMV) (V)	–	–	–	H	0
HORTICULTURAL CROPS						
Apple (*Malus domestica* Borkh.)						
Apple scab	*Venturia inaequalis* (F)	—	—	–	B;EM	–
Bitter rot	*Glomerella cingulata* (F)	+	—	–	B;EMN	–
Black rot	*Botryosphaeria obtusa* (F)	+	—	–	B;EM	–

Table 1 (*continued*).

		Effect of climate change[b]				
Crop and disease	Pathogen (group)[a]	Primary inoculum or disease establishment	Rate of disease progress	Potential duration of epidemic[c]	Reasons for effects[d]	Net effect on disease[e]
Cedar–apple rust	*Gymnosporangium juniperi-virginiana* (F)	–	—	–	D;EM	–
Collar rot	*Phytophthora cactorum* (F)	+	—	–	AB;KN	–
Fly speck	*Zygophiala jamaicensis* (F)	+	—	–	B	–
Powdery mildew	*Podosphaera leucotricha* (F)	+	+	–	B;FL	+
Fire blight	*Erwinia amylovora* (B)	+	—	–	B;ELMN	0
Grape (*Vitis* spp.)						
Black rot	*Guignardia bidwellii* (F)	+	—	–	B;M	–
Bunch rot	*Botrytis cinerea* (F)	+	—	–	B;EL	–
Cane and leaf spot	*Phomopsis viticola* (F)	+	—	–	B;MN	–
Dieback	*Eutypa lata* (F)	+	—	–	B;EN	–
Downy mildew	*Plasmopara viticola* (F)	+	—	–	B	–
Powdery mildew	*Uncinula necator* (F)	+	+	–	F	+
Crown gall	*Agrobacterium tumefaciens* (B)	–	–	–	AC;N	0
Peaches (*Prunus persica* (L.) Batsch.)						
Brown rot	*Monilinia fructicola* (F)	+	—	–	B;ELN	–
Canker	*Cytospora leucostoma* (F)	+	—	–	B;EGLN	+
Plum pox	*Plum pox virus* (PPV) (V)	–	+	–	C;HI	+
Strawberries (*Fragaria ananassa* Duch.)						
Anthracnose	*Colletotrichum* spp. (F)	+	—	–	BC;E	–
Common leaf spot	*Mycosphaerella fragariae* (F)	+	—	–	AB;EM	–
Grey mold	*Botrytis cinerea* (F)	+	—	–	AB;E	–
Leaf blight	*Phomopsis obscurans* (F)	+	—	–	B;MO	–
Leaf scorch	*Diplocarpon earlianum* (F)	+	–	–	B;O	0
Leather rot	*Phytophthora cactorum* (F)	–	—	–	A;EKO	– –
Powdery mildew	*Sphaerotheca macularis* (F)	+	+	–	B;F	+
Angular leaf spot	*Xanthomonas fragariae* (B)	+	—	–	B;EM	– –
Root lesion	*Pratylenchus* spp. (N)	–	+	–	A;G	+
Turf						
Anthracnose	*Colletotrichum graminicola* (F)	+	+	–	B;G	+
Brown patch	*Rhizoctonia solani* (F)	–	+	–	B;GF	–
Dollar spot	*Sclerotinia homoeocarpa* (F)	+	+	–	B;GF	+
Foliar blight	*Pythium aphanidermatum* (F)	—	—	–	A;EG	–
Fusarium patch	*Microdochium nivale* (F)	+	—	–	B;E	–
Melting-out	*Drechslera* spp. (F)	+	–		B	–
Necrotic ring spot	*Leptosphaeria korrae* (F)	+	—	–	B;EG	–
Powdery mildew	*Erysiphe graminis* (F)	+	–	–	B	0
Red thread	*Laetisaria fuciformis* (F)	–	—	–	A;E	–
Root rot	*Pythium* spp. (F)	—	—	–	A;EG	–
Rust	*Puccinia* spp. (F)	+	+	–	BD	+
Summer patch	*Magnaporthe poae* (F)	+	—	–	B	–
Take-all patch	*Gaeumannomyces graminis* (F)	+	—	–	B;GK	+
Typhula blight	*Typhula* spp. (F)	+	—	–	AB;E	– –
FOREST TREES						
Ash (*Fraxinus* spp.)						
Forest decline		+	+	–	GK	++
Beech (*Fagus* spp.)						
Beech bark disease	*Nectria coccinea* var. *faginata* (F)	+	+	–	HN	+
Elm (*Ulmus* spp.)						
Dutch elm disease	*Ophiostoma ulmi* (F)	+	+	–	CFI	+
Larch (*Larix* spp.)						
Larch canker[f]	*Lachnellula wilkommii* (F)	—	—	–	E	–
Maple (*Acer* spp.)						
Forest decline		+	+	–	GK	++

Table 1 (*concluded*).

		Effect of climate change[b]				
Crop and disease	Pathogen (group)[a]	Primary inoculum or disease establishment	Rate of disease progress	Potential duration of epidemic[c]	Reasons for effects[d]	Net effect on disease[e]
Oak (*Quercus* spp.)						
Forest decline		+	+	–	GK	++
Oak wilt[f]	*Ceratocystis fagacearum* (F)	+	+	+	FIK	+
Pine (*Pinus* spp.)						
Armillaria root rot[g]	*Armillaria* spp. (F)	–	+	+	F	+
Blue stains	*Ophiostoma* spp. (F)	+	+	–	C;FH	+
Diplodia canker	*Sphaeropsis sapinea* (F)	–	+	–	G	+
Fomes root rot	*Heterobasidion annosum* (F)	+	–	+	B;FN	++
Scleroderris canker European race	*Ascocalyx abietina* (F)	—	—	–	E	–
White pine blister rust	*Cronartium ribicola* (F)	—	—	—	EM	–
Pine wood nematode	*Bursaphelenchus xylophilus* (N)	–	+	+	FGH	+
Dwarf mistletoe[f]	*Arceuthobium americanum* (PL)	–	–	+	F	+
Poplar (*Populus* spp.)						
Conifer–aspen rust	*Melampsora medusae* (F)	—	—	–	M	–
Hypoxylon canker	*Hypoxylon mammatum* (F)	+	+	–	L	+
Spruce (*Picea* spp.)						
Tomentosus root rot	*Inonotus tomentosus* (F)	–	+	–	F	+

[a]Pathogen group: B, bacteria; F, fungus; N, nematode; P, phytoplasma; PL, parasitic plant; V, virus. Taxonomic authorities for names of organisms are the same as presented by the American Phytopathological Society (2004), Rossman et al. (1987), or Couture et al. (2003).
[b]Anticipated increase (+), decrease (—), or no change (–).
[c]Anticipated effect of increased duration of growing season on disease.
[d]Reason(s) for anticipated changes are listed first for primary inoculum and disease establishment, and then, following a semicolon, for rate of disease progress. Initial or primary inoculum: A, soilborne and expected to remain at the same levels, or possibly decrease, as a result of milder winters, longer growing season, and (or) increased microbial competition; B, debris-borne or survives on host and expected to increase because of increased survival over milder winters; C, insect-borne and expected to increase because of increased survival of insect vectors; D, introduced each year from outside sources, i.e., seed-borne, airborne. The influence of climate change is difficult to assess without knowledge of the pathogen, host, and source of inoculum. Warmer and (or) drier growing season slows rate (E) or increases rate (F) of disease progress. G, severity of disease symptoms increases because of stress of drier and (or) warmer summer growing conditions; H, survival of insect vectors increases because of milder winter; I, rate of development of insect vectors increases because of warmer temperatures; J, earlier introduction of vectors or pathogens from southern regions; K, reduced soil moisture because of increased evapotranspiration, sporadic precipitation, etc., affects pathogen; L, increased wound sites on hosts because of increased extreme weather events (i.e., thunderstorms, high winds, hail) and (or) increased insect damage increases infection sites; M, reduced disease development and spread because of decrease in rain and (or) length of time of leaf wetness; N, fruiting bodies on trees have a longer active growth period in both fall and spring, hence more primary inoculum; O, on nonwoody perennials, pathogens have longer to grow on roots or overwintering leaves so more damage and perhaps increased primary inoculum in spring.
[e]Net anticipated effect on a particular plant disease. From a significant decrease (– –) to a significant increase (++) in importance (– –, –, 0, +, ++).
[f]In North America but not yet in Ontario.
[g]Affects all tree species.

et al. 2003). All of these diseases, introduced or native, are influenced by climate to varying degrees. Warmer and drier conditions will likely reduce the incidence of diseases such as white pine blister rust and scleroderris canker that require cool, wet conditions for infection, and in the case of scleroderris canker, an extended cold period (Marosy et al. 1989; Van Arsdel et al. 1956). However, warmer and drier conditions will likely increase the damage caused by root rots, particularly by *Heterobasidion annosum*, which is restricted in its range by a cooler climate. Similarly, diseases such as oak wilt, which have had a serious impact on oak species in the United States (Wilson 2001) and which are found in states adjacent to Ontario, would benefit from warmer drier conditions. Facultative pathogens, causing diseases such as armillaria root rot, and wilt diseases, such as verticillium wilt and those caused by pine wood nematode (*Bursaphelenchus xylophilus* (Steiner & Buhrer) Nickle), as well as secondary canker-causing fungi would benefit from the heat and drought stress caused to forest and urban trees (Schoeneweiss 1975). The increased frequency of wind and ice storms will make forests more susceptible to breakage and mortality as well as to decays.

Bacterial diseases

Soilborne, bacterial plant pathogens, such as *Agrobacterium tumefaciens*, build up their populations in host plants and are released into the soil where they can survive to act as primary inoculum the next season (Agrios 1997; Lucas 1998; Trigiano et al. 2004). Host or debris-borne bacteria survive on and in host tissues. On perennial hosts, bacteria, such as *Erwinia amylovora* on apple, overwinter on infected host tissue, and primary inoculum is spread from host to host the next season. On annual hosts, bacteria such as *Pseudomonas syringae* pv. *phaseolicola* (= *P. savastanoi* pv.

phaseolicola (Burkholder) Gardan et al.) survive in host debris in soil or on the soil surface. Vector-borne bacterial pathogens, such as *Erwinia stewartii* (example 3), survive in insect vectors, and these vectors act as the source of primary inoculum the next season. Introduced bacterial pathogens, such as *Pseudomonas syringae* pv. *tomato* and *Xanthomonas campestris* pv. *vesicatoria* (= *X. vesicatoria* (Doidge) Vauterin et al.) (example 4), arise from infected seed and possibly also survive in debris, soil, and weeds. Milder, shorter winters are expected to have little effect on soilborne bacterial pathogens; however, survival of host or debris-borne and vector-borne primary inoculum is expected to increase. The effect on primary inoculum of pathogens introduced on seed is difficult to estimate.

Most bacterial diseases are considered polycyclic. Bacteria are spread to their host plants mainly by water, usually in the form of rain splash, and insects. Moisture is the most important factor in the development of bacterial diseases (Agrios 1997). Abundant moisture increases multiplication, oozing, and spread of bacteria. In humid, wet conditions, infected plant tissues can exude masses of bacteria that are spread from host to host by rain splash and insects. Therefore, the warmer drier summers expected with climate change should limit bacterial diseases. However, bacteria often enter their plant hosts through wounds (Agrios 1997; Trigiano et al. 2004), and the expected increase in frequency and intensity of summer storms with high winds, rain, and hail will increase wounding of plants and provide moisture for the spread of bacteria.

Viral diseases

Primary inoculum can be host-borne and overwinter in perennial hosts for plant diseases caused by viruses (e.g., *Plum pox virus* (PPV)). Introduced viruses arrive in seed (e.g., *Bean common mosaic virus* (BCMV) and *Soybean mosaic virus* (SMV)) or in tissues of plants used for vegetative propagation (e.g., *Potato leafroll virus* (PLRV) (example 5) and PPV) (Agrios 1997; Trigiano et al. 2004).

Although vectors do not play a role in the primary inoculum of viruses, they are important in the spread of viral diseases (Brunt et al. 1996). Vectors of viruses include insects, especially aphids (e.g., SMV, BCMV, PPV, *Bean yellow mosaic virus* (BYMV), PLRV, and *Cucumber mosaic virus* (CMV)), and nematodes (e.g., *Tobacco ringspot virus* (TRSV)). Mechanical injury is also an important way that viruses can spread between plants (e.g., *Tobacco mosaic virus* (TMV)).

The severity of viral diseases is determined in large part by the amount of inoculum and the time of infection. The amount of virus inoculum is influenced by winter survival of its (alternate) plant host(s), winter survival of its transmission vector, whether the virus vector can transmit the virus throughout its life (e.g., persistent) or not, and by the rate of accumulation and spread of the transmission vector (Irwin et al. 2000; Jayasena and Randles 1994).

Infection of plants at an early developmental stage usually leads to more severe disease symptoms, e.g., SMV (Ren et al. 1997; Schulz et al. 1983); PLRV (Storch and Manzer 1985); BCMV (Gupta and Chowfla 1987). For some viruses, higher temperatures also cause more severe symptoms development (Wu et al. 1993).

Insects such as aphids are expected to have increased survival with milder winter temperatures, and higher spring and summer temperatures will increase their development and reproductive rates and lead to more severe disease (Alonso-Prados et al. 2003). Milder winters are also expected to increase survival of alternate weed hosts of viruses. Increases in frequency and intensity of summer storms with high winds, rain, and hail will increase wounding of plants and result in increased transmission of viruses by mechanical means. Therefore, with predicted changes in climate in Ontario, viral diseases of plants are expected to increase in importance.

Potentially of greater importance will be the effects of diseases caused by new, introduced viruses that, because of the changed climate, will be able to persist. A warmer climate might also allow viruses that are present in greenhouses, such as *Pepino mosaic virus* (PepMV), to establish infection in the field (French et al. 2001).

Nematodes

The majority of plant-pathogenic nematodes spend part of their lives in soil, and therefore, soil is the source of primary inoculum (Agrios 1997; Trigiano et al. 2004). The life cycle of a nematode can be completed within 2–4 weeks under optimum environmental conditions. Temperature is the most important factor, and development is slower with cooler soil temperatures. Overwintering of nematodes is not expected to be significantly affected by changes in climate, although for some, such as the soybean cyst nematode (example 6), egg viability may be reduced in mild winters. Warmer soil temperatures are expected to accelerate nematode development in Ontario, perhaps resulting in additional generations per season, and drier temperatures are expected to increase symptoms of water stress in plants infected with nematodes such as the soybean cyst nematode. Overall, diseases caused by nematodes are expected to increase in importance in Ontario with expected climate changes.

Phytoplasmas

Phytoplasmas overwinter in perennial hosts, and this is the source of primary inoculum (Agrios 1997). Insect vectors feed on infected plants, acquire the phytoplasma, and transmit it to healthy plants. In Ontario, aster yellows (example 7) is the most important disease caused by a phytoplasma.

Milder winters will result in increased survival of infected perennial weedy hosts of phytoplasmas. Survival of insect vectors is expected to increase with milder winter temperatures, and higher summer temperatures will increase their development and reproductive rates. Therefore, with climate change, phytoplasmas such as aster yellows phytoplasmas are expected to become more important in Ontario.

Abiotic diseases or disease complexes

Abiotic plant diseases are caused by noninfectious factors such as nutrient deficiencies, air pollutants, and temperature and moisture extremes (Agrios 1997; Trigiano et al. 2004). Such abiotic diseases can have direct and indirect effects on plant health. Direct effects include the development of disease symptoms directly related to a deficiency or excess of a physical factor such as moisture, heat, or nutrients. Toxic effects are another example of a direct effect and can be caused by inappropriate use of pesticides or chemical pollutants to which plants are intentionally or unintentionally exposed.

Biotic diseases can also result from indirect effects, where plants have their defenses weakened by an abiotic factor and are predisposed to infection by plant pathogens. Several important plant diseases are initiated by abiotic stress(es), including forest decline diseases, which are an example of a disease complex caused by a combination of plant predisposition and a repetitive sequence of plant stresses that weaken a plant until it becomes susceptible to weak pathogens that then can often infect and kill the plant (Manion 1991; Manion and Lachance 1992). These weak pathogens, called saprogens, are often ubiquitous inhabitants of soil and decaying plant material and, normally, they do not cause disease in healthy, unstressed plants. However, under conditions of environmental stress, plants can become susceptible to these saprogens and their opportunistic infections. One of the more prevalent examples of these saprogens is the girdling fungi of the genus *Armillaria* (Manion and Lachance 1992). As climate changes develop, new combinations of host–stress–saprogens will be encountered and might give rise to new types of decline diseases, particularly in tree species. In temperate climates, plants that are stressed by biotic or abiotic factors during a growing season are often predisposed to freezing damage during the subsequent winter.

Plant diseases associated with interactions of biotic and abiotic diseases, or disease complexes, are a unique and important area of consideration for assessing the influence of climate change on plant diseases. In particular, forest declines are an example of plant diseases that result from a combination of interacting biotic and abiotic factors; they are often referred to by their symptom syndrome, such as dieback or decline. Such diseases are characterized by a variety of disease symptoms and signs, are typically scattered in a random pattern throughout a population within a region, and are often host-specific, although more than one tree species in a region may have its own specific decline symptoms. Decline diseases are one example where a strong association between climate change and disease incidence and (or) severity has already been established in several forest species (Manion and Lachance 1992). Episodes of extensive forest declines have been documented in Europe and North America in ash, birch (*Betula* spp.), balsam fir (*Abies balsamea* (L.) Mill.), and maple (Innes 1993; Millers et al. 1989), and a strong relationship was evident between climate warming in the Northern Hemisphere and the onset of crown dieback in 1925, 1937, and 1981 on selected species of northern hardwoods in eastern Canada (Auclair et al. 1992).

Mitigation of effects of climate change on plant diseases in Ontario

The development of several extreme weather events in recent years, such as ice storms, droughts, and hurricanes, have highlighted a growing body of social awareness and scientific evidence that our climate is changing, both globally and locally. The final report *Climate Change: We Are at Risk* of the Standing Committee on Agriculture and Forestry recently concluded that our climate is indeed changing, and that these changes will influence Canada's agriculture, forests, and rural communities (Senate of Canada 2003).

With significant and relatively rapid changes in climate in Ontario, there will be an acceleration in the number of new crops and cultivars introduced to the province. The adaptation of agronomic and horticultural cultivars to regional soil and climatic conditions is a well-established practice that involves comparing agronomic performance in multiple locations over multiple years. Only cultivars that perform well, on average, across these locations and environments are selected for commercial use. This process of agronomic adaptation of plant genotypes appropriate for Ontario has been highly successful for many years and will be instrumental in continuing to select adapted cultivars under expected climate changes. One note of concern, however, is that this process might not be effective for erratic and extreme weather events that are predicted with climate change in Ontario.

Increased emphasis should be placed on breeding plants for environmental stress tolerance, such as drought stress. Tolerance or resistance of crops to environmental stresses will result in healthier crops that are better able to resist disease and produce improved yields. New techniques that enhance the identification and development of host tolerance or resistance to biotic and abiotic diseases will be important in facilitating this adaptation.

An increase in the number of new introduced plant diseases is also expected to accompany climate change. It will be important to have diagnostic tools and adequate personnel to detect new pathogens that might be harbored in these introductions. Recently, McKenney et al. (2003) used prediction of changes in temperature and precipitation to determine the risk of spread of several introduced tree diseases, and such models can also contribute to the process of risk assessment of climate change and changes in the distribution of pathogens and diseases.

Drier soils and irregular precipitation will result in increased use of irrigation. This will be economically feasible primarily with higher-value crops such as vegetable, horticultural, and specialty crops. Technology for efficient irrigation could be adapted from those already used in arid climates. Water conservation systems may also contribute to reduced leaf wetness and humidity in the crop canopy and, therefore, contribute to reduced foliar disease compared with more traditional practices such as overhead irrigation.

Because of the long-lived nature of trees, and accordingly the limited degree to which adaptation can occur, it will be increasingly necessary to consider these impacts in forest management plans, including species selection, breeding, and site selection. Forest declines could become more extensive and common because of the inciting factors of drought and the potential for variable winter temperatures (e.g., freeze–thaw events). Drought-prone sites might be abandoned in terms of commercial forestry, and shortrotation species such as hybrid poplars might take on an increased importance for fiber production.

Unlike forest trees, most of the commercially grown crops in Ontario, with the exception of fruit trees, are annuals or short-lived perennials. Thus, appropriate cultivars and cultural practices will evolve as climate change occurs. Indeed, over the period of time involved, we will undoubtedly see wide-scale changes in the crops grown, just as has occurred in Ontario in the past 100 years. However, the rate of change in plant agriculture is expected to accelerate with changes in climate. In the past, continuous input from agronomists, plant breeders, and pest management specialists was essential to the success of plant agriculture in Ontario. This system of research and adaptation must not be eroded. With the potential effects of climate change, crop research will become more important than ever. We have remained abreast of many changes because of the dedicated work of those who have gone before us. Change will occur more rapidly than ever before, and the research structure must be in place to meet future challenges.

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Appendix

Example 1: *Sclerotinia sclerotiorum* (Lib.) de Bary, a soilborne, fungal pathogen with a wide host range

This fungal pathogen can cause disease in more than 400 plant species (Boland and Hall 1994). In Ontario, *S. sclerotiorum* is particularly severe in bean, canola, carrot, lettuce, and soybean but, depending on environmental conditions, can also be severe in potato, tomato, and forage crops such as alfalfa and clover. Crop losses ranging from 25% to 50% are commonly reported in various crops in severe, localized outbreaks; however, on average, crop losses of 2%–7% are a reasonable estimate in bean, canola, and soybean. Given the economic value of these crops in Ontario in 2000, such crop losses would be valued at annual losses of up to $\$40 \times 10^6$ (farm value at 7% loss).

Sclerotinia sclerotiorum spends at least 95% of its life cycle in and on soil as sclerotia. Under conditions of moist soil and cool soil temperatures, sclerotia germinate to produce fruiting structures called apothecia, which release ascospores into the air. Ascospores require moisture and cool to moderate temperatures to initiate disease.

Sclerotia are hardy survival structures. Milder winters may increase survival, while increased freeze–thaw cycles and microbial activity may decrease survival. Therefore, with changes in climate, there might not be significant differences in survival of sclerotia over winter. Warmer, drier conditions that are expected, over the growing season, with climate change in Ontario will result in an environment that is less conducive to production of apothecia and infection by ascospores. Overall, severity of diseases caused by *S. sclerotiorum* is expected to decrease in Ontario with the effects of climate change.

Example 2: *Phaeoisariopsis griseola* (Sacc.) Ferr., a debris-borne, fungal pathogen that was recently introduced to Ontario

This fungal pathogen causes angular leaf spot of bean (ALS), which is primarily a disease of the tropics and subtropics. Angular leaf spot is considered to be of minor importance in most bean-producing areas of the northern United States, although it can cause epiphytotics when conditions are suitable. In the northern United States, yield losses of 50% have been reported (Hagedorn and Wade 1974). Angular leaf spot was first reported in Canada in 2000 on snap beans, and the pathogen overwintered on crop debris causing disease in 2001 (Melzer et al. 2001).

Primary inoculum for ALS is debris- and seed-borne, however, overwintering fungal tissue in host debris is considered the main source of primary inoculum. Milder winters should result in increased survival of *P. griseola*. In addition, the pathogen survives better in surface debris than when buried (Correa and Saettler 1987). Higher temperatures and greater evaporation are expected to result in greater use of conservation and zero tillage to conserve soil moisture, which will result in more debris on the soil surface. Therefore, the ability of *P. griseola* to overwinter in Ontario is expected to increase with climate change.

Rate of disease progress for ALS in a changing climate is difficult to assess because it has just established in Ontario. The pathogen's requirement for rain or high humidity for production of spores and for infection suggests epidemics that will start in the moist spring and early summer, will slow during the hotter, drier summer months, and will resume again in the late summer.

Length of the growing season is an important factor in epidemics of polycyclic diseases. Bean growers are expected to take advantage of longer growing seasons, and this would result in longer epidemics, higher final disease incidence and yield loss, and increased stromata to overwinter and produce primary inoculum in the next season.

Angular leaf spot, a new disease to Ontario, has the potential to become a significant disease of bean in this province because of increased survival over milder winters and a longer season for epidemics to develop.

Example 3: *Erwinia stewartii* (= *Pantoea stewartii* ssp. *stewartii* (Smith) Mergaert et al.), causal agent of Stewart's disease of corn, a bacterial disease spread by an insect vector that is becoming more prevalent in Ontario

This bacterium causes Stewart's disease of corn. It is vectored by insects, and the predominant vector in Ontario is the corn flea beetle (*Chaetocnema pulicaria* Melsh.). The bacterium overwinters in the digestive tract of beetles. The cold winters in Ontario usually kill most beetles; however, there have been occasional outbreaks of this disease in Ontario since 1932, and the mild winters in 1998 and 1999 led to the most severe outbreaks of Stewart's disease recorded in Ontario.

Primary inoculum is dependent on survival of flea beetles, and the number of flea beetles emerging from hibernation in spring depends on winter temperatures. Primary inoculum is spread when infested beetles that survive the winter feed on corn seedlings in spring. Plants affected early in the season (before they reach 60 cm tall or five-leaf stage) are most severely affected and suffer 40%–100% yield loss. Plants infected later in the season usually have less than 10% yield loss. Disease severity is generally increased by high temperatures (Hershman et al. 2003).

The predicted higher winter temperatures associated with climate change would result in increased survival of corn flea beetles, the source of primary inoculum for Stewart's disease. Summers are expected to be drier, and flea beetles prefer dry weather and do poorly in prolonged wet periods. In addition, severity of Stewart's disease is increased by high temperatures. This suggests that, in Ontario, the occurrence and severity of Stewart's disease will increase with predicted changes in climate.

Example 4: *Pseudomonas syringae* pv. *tomato* (Okabe) Young et al. and *Xanthomonas campestris* pv. *vesicatoria* (= *X. vesicatoria* (Doidge) Vauterin et al.), causal agents of bacterial spot and bacterial speck of tomato, respectively; two common bacterial diseases of tomato

These bacteria cause bacterial speck and bacterial spot of tomato, two diseases that have become increasingly problematic for growers throughout North America. In Ontario, both pathogens are thought to be introduced on contaminated seed (Louws et al. 2001) and may also survive in soil, on plant debris, or on other weedy hosts, as reported for the southern United States (Jones et al. 1986; McCarter et al. 1983). Healthy tomato transplants have varying levels of these bacteria growing epiphytically on their surface, but the severity of disease in the field is more dependent on environmental conditions than on the population size of epiphytic bacteria at the time of transplanting (Cuppels and Elmhirst 1999).

Based on the predicted warmer and drier summers of the future, the severity of bacterial spot and bacterial speck might be expected to decrease because of the requirement for moisture and high humidity. This reduction might, however, be counteracted by the possibility of enhanced survival of the bacteria in crop residue and soil, and as epiphytes on weeds during the milder winters. The role of severe rain and wind storms in facilitating the entrance of these bacteria into the leaf, and the subsequent initiation of disease, will probably be a more critical factor in crop losses due to speck and spot. If the relative humidity early in the season, or later within the canopy, is high enough to allow sufficient epiphytic growth of these pathogens, the increased frequency and severity of such storms will increase the likelihood of severe disease episodes. Overall, the incidence of disease might be less frequent, but when infection would occur, the amount of damage could be high.

Example 5: *Potato leafroll virus* (PLRV), an insect-vectored, viral pathogen of potato and other crops

PLRV infects many plants including potato, tomato, tobacco, bean, alfalfa, onion, apple, strawberries, turf, and peach (Brunt et al. 1996). It belongs to the genus *Luteovirus* and is transmitted by a variety of aphids, in particular the green peach aphid (*Myzus persicae* (Sulz.); Thomas et al. 1997). After an aphid has acquired the virus from a PLRV-infected plant, it is capable of transmitting it for the rest of its life. Spread of the virus among plants within a field, and between fields, can be by the winged forms of the aphid, but much of the spread within a field is accomplished by the wingless forms (Brunt et al. 1996). Once the virus has been introduced to a plant by feeding aphids, the virus spreads from leaves to tubers. Crops planted with these tubers can be severely stunted, resulting in severe yield losses and poor tuber quality. Browning of the vascular system of the tuber (net necrosis) may not develop prior to harvest but typically does develop upon further storage (Pasche et al. 2003).

A large percentage of PLRV was related to the amount of primary inoculum and the thermal unit accumulation (Thomas et al. 1997; DiFonzo et al. 1994). The latter is due to the effect of temperature on the development and the optimal temperature for the flight of winged forms of the aphids.

The milder winters, which are expected to result from climate change in Ontario, are likely to increase primary inoculum by increasing the winter survival of infected host plants. In addition, more aphid vectors will survive the winter and result in acquisition of virus and infection of plants earlier in the year. Also, under warmer temperatures, more aphids will develop over a longer period, and winged forms will find optimal temperatures for flight on more occasions. Taken together it is, therefore, expected that PLRV will increase as a result of predicted climate change.

Example 6: *Heterodera glycines* Ichinohe, the soybean cyst nematode, continues to spread in southern Ontario

The soybean cyst nematode (SCN), first detected in Ontario in 1987, is the major economically limiting disease problem of soybeans in North America. Larvae penetrate soybean roots and feed in the vascular system until they become adults. The adult male exits the root and swims to mate with lemon-shaped adult females that protrude from the root. Some of the fertilized eggs are released immediately and give rise to new generations of larvae in that growing season. The remaining eggs (several hundred) are retained in the female body, which matures into a cyst that may survive up to 9 years in the soil.

Yield reductions caused by feeding nematodes are largely due to decreased root growth and the consequent reduction in water and nutrient uptake. Reduced nodulation by nitrogen-fixing bacteria also results in reduced nitrogen fixation. Often, no symptom other than reduced growth is seen, and even this symptom may be overlooked if the entire crop is infected. In more extreme situations, symptoms typical of nutrient and water deficiencies appear with yields further reduced.

Various stages in the disease cycle of SCN are differentially affected by temperature and moisture. The highest winter survival of SCN eggs occurs in the colder areas of the continent. Thus, spring inoculum levels may be the highest in the northern range of soybean culture. Optimal soil temperatures for egg hatch, root penetration, and juvenile and adult development are 24, 28, and 28–32 °C, respectively, while below 15 °C and above 35 °C, little development occurs (Chen et al. 2001). Temperature can thus affect the number of SCN generations per growing season. In theory, at least, with fewer generations, new races will build up less quickly.

In Ontario, predicted temperature increases per se might be expected to have a limited effect on yield loss caused by SCN. The more moderate winter temperatures will reduce egg survival, while the higher temperatures in the growing season will increase egg hatch, the rate of nematode infection and development, and the number of generations per season. Soil water is important in the movement and development of SCN, but water is unlikely to be a limiting factor early in the season. In contrast, the drier growing conditions of summer will increase yield loss due to SCN because of the reduced root surface. This latter effect is predicted to be the most important.

Example 7: aster yellows phytoplasma, an insect-vectored pathogen with a wide host range

This pathogen has over 300 hosts in 50 plant families. Cultivated crops that can be affected by aster yellows include carrot, celery, cucurbits, potato, sage, tomato, echinacea, canola, flax, barley, wheat, oats, rapeseed, sunflower, and faba beans. Weed hosts include chickory (*Cichorium intybus* L.), knotweed (*Polygonum* spp.), lamb's-quarters (*Chenopodium album* L.), pineappleweed (*Matricaria matricarioides* (Less.) Porter), plaintain (*Plantago* spp.), quack grass (*Agropyron repens* (L.) Beauv.), ragweed (*Ambrosia* spp.), stinkweed (*Thlaspi arvense* L.), sow-thistle (*Sonchus* spp.), wild asters, and wild carrot (*Daucus carota* L.) (Manitoba Agriculture, Food and Rural Initiative 2001).

The aster yellows phytoplasma overwinters in perennial hosts, and this acts as the primary inoculum. Aster leafhoppers (*Macrosteles quadrilineatus* Fbs.) are vectors of the pathogen and move the primary inoculum to healthy plants when they feed. Primary inoculum can also be introduced when leafhoppers carrying the aster yellows phytoplasmas are blown into Ontario from the United States (Chaput and Sears 1998).

Milder winter temperatures expected with climate change would result in increased survival of perennial hosts and leafhopper eggs. This would result in more primary inoculum and more vectors for the primary inoculum. Warmer temperatures the rest of the year would result in increased development and reproduction of the vector. In addition, symptoms of aster yellows tend to increase with increasing temperature. Therefore, aster yellows might become a more important disease in Ontario with expected changes in climate.

Example 8: maple decline, a disease complex known to be associated with climate change

Decline diseases are generally viewed as deterioration in tree health over a large area with evidence of decreased growth rate, increasing branch dieback, and above-normal tree mortality. The most familiar decline disease in Canada is maple decline. Often, it is not a single event or stress that leads to decline diseases such as maple decline but a "disease complex" of several interacting predisposing (e.g., site characteristics such as soil nutrients or climate), inciting (e.g., several years of excessive drought or precipitation), and contributing (e.g., insect defoliation or weak plant pathogens) factors that progressively stress individual trees until they weaken and die.

In a changing climate, increased temperature and evapotranspiration, as well as an increased frequency of extreme weather events such as ice storms or wind storms, will increase stress to forests and potentially increase the frequency of forest declines. Recently, extensive damage to sugar maple forests was reported following an ice storm that affected much of northeastern North America (Smith 2000). In Ontario, over 604 000 ha of hardwood forest made up largely of sugar maple (*Acer saccharum* Marsh.) were damaged directly by this event (Hopkin et al. 2001a).

Storm damage like this, or wind events, are predicted to become more frequent under climate-change models. Such events cause immediate damage but can also predispose trees to fungi and insects that can cause additional long-term loss of vigor and mortality (Hopkin et al. 2001b). Ground-level pollutants such as ozone, which has also increased in recent years, can add to these forest stresses (McLaughlin and Percy 1999).

Given the predicted changes in climate for Ontario, significant increases in tree decline diseases are anticipated. Increased temperatures and evapotranspiration, as well as an increased frequency of extreme weather events such as wind, hail, and ice storms, will increase the frequency and severity of stress factors leading to maple and other forest declines.